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HEAT-ACTIVATED HEAT-PUMP DEVELOPMENT AND POTENTIAL APPLICATION OF STIRLING-ENGINE TECHNOLOGY

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ABSTRACT

This paper presents a brief overview of the heat-activated heat pump technology development program being carried out by Oak Ridge National Laboratory (ORNL), for the Department of Energy's Building Equipment Research Division with emphasis on the Stirling engine technology projects. This paper 1) reviews the major projects as they were formulated and carried out under the previous "product development" guidelines, 2) discusses the revised technology development focus and current status of those major hardware projects, 3) presents our assessment of the key issues involved in applying Stirling engine technology to heat pump equipment, and 4) describes the approach and planned future activities to address those issues. For completeness, the paper also includes brief descriptions of two projects in this area supported by the Gas Research Institute (GRI).

*Research sponsored by the Office of Buildings Energy Research and Development, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

HEAT-ACTIVATED HEAT PUMP DEVELOPMENTS

At ORNL we have been conducting inhouse research on heat pumps since 1976 and since 1978 we have been assisting DOE in managing a contracted R&D program involving advanced residential and commercial heat pump technologies. A major portion of the DOE/ORNL contracted R&D resources has been allocated toward development of heat-activated heat pumps. The rationale for this is based on the potential fuel efficiency improvement such a product could offer in combination with a large market potential.

Program Rationale and Project Makeup

Conventional combustion heating equipment (gas or oil furnace, for example) currently achieves about 75% efficiency and, when developed to its ultimate potential, can approach but not exceed 100% efficiency. Heat-activated heat pumps, of which the gas-fired heat pump is the predominant example, offer a potential heating coefficient of performance (COP) exceeding 1.0, that is, delivering a heating effect greater than the heating value of the input fuel. A gas heat pump currently envisioned as a typical 1990's residential product should use 30 to 50% less gas than the advanced gas furnace, as illustrated in Fig. 1.

With regard to market potential, about 55% of the nation's 75 million homes are heated using natural gas, as shown in Fig. 2. Furnaces and other gas heating appliances generally have a 15-20 year life expectancy, which creates a continuing replacement/retrofit market of about a million units per year. With addition of new homes, the potential market in residential heating alone is estimated at approximately 1.5 million units annually. With the cooperative support of the gas utility industry, the gas heat pump is emerging as an important option for improved fuel efficiency in residential and commercial buildings in the 1990's if its viability in the marketplace can be established.

ORNL-DWG 82-15456

FUEL UTILIZATION OF ALTERNATIVE HEATING SYSTEMS

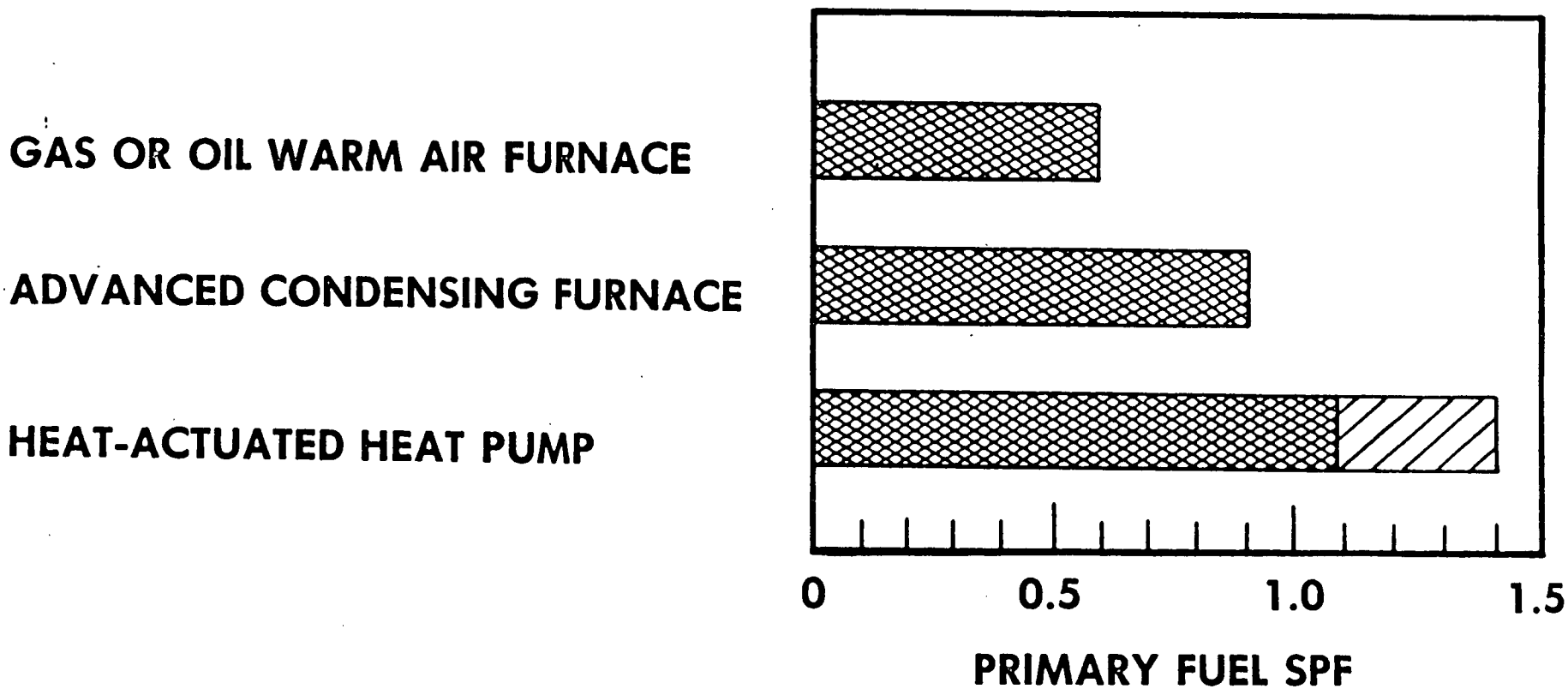
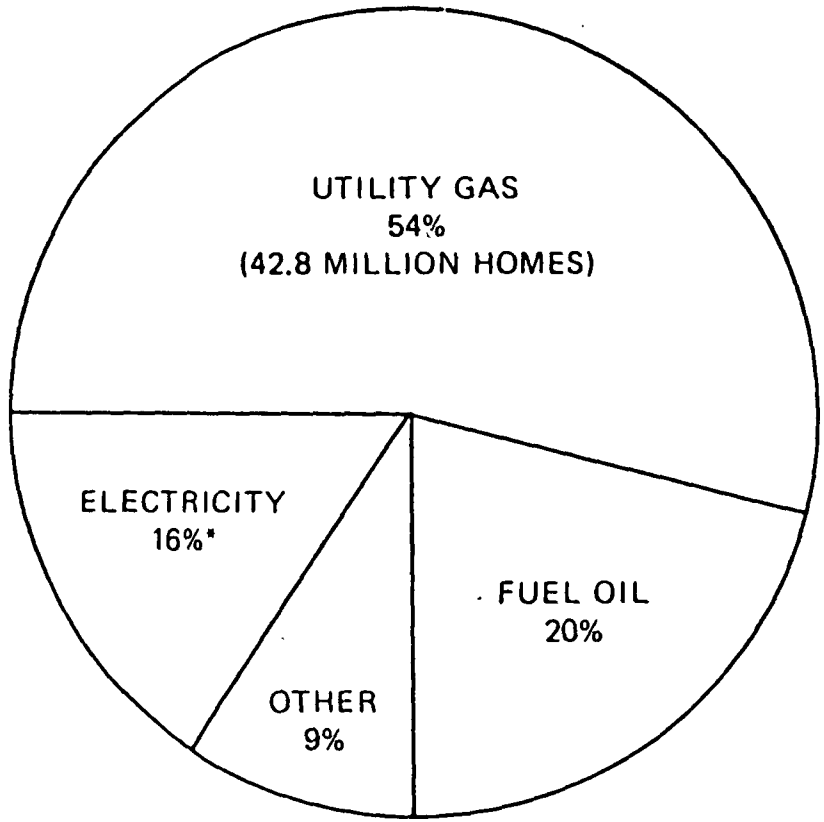


Figure 1.

ORNL–DWG 81-6393

DISTRIBUTION OF HOME HEATING ENERGY SOURCES
(78.6 MILLION HOMES)



*ELECTRIC HEAT PUMPS INSTALLED IN APPROXIMATELY 2 MILLION HOMES (3% OF TOTAL HOMES)

SOURCE: AIR CONDITIONING, HEATING, AND REFRIGERATION NEWS, JULY 23, 1979/APRIL 7, 1980/JANUARY 5, 1981 ISSUES

Figure 2.

There are two basic types of heat-activated heat pumps. The first uses an absorption cycle and the second replaces the electric motor of the conventional electric heat pump with a fueled prime mover (engine-driven). Of course, one of the key advantages of the heat-activated system is that in the heating mode, waste heat can be recovered to augment the heating effect produced by the heat pump cycle, as shown in Fig. 3, thus increasing the heating capacity and COP significantly. In most cases, systems developed for use with natural gas can also be oil-fired with appropriate modifications to the combustion system.

Development projects to date have included two absorption and four heat engine-driven heat pump concepts. The general strategy when these major projects were selected involved supporting different concepts with differing levels of risk and ultimate performance potential. Absorption heat pump technology was viewed as being more well-established and, thus lower risk, because of similar commercially available equipment (i.e., absorption chillers and gas air conditioners). However, it offered only moderate fuel efficiency improvement. Heat-engine-driven technology, on the other hand, seemed to entail higher technical and business risk, but offered more dramatic performance gains. Table 1 compares the assessed risk and efficiency objectives for the concepts selected for major prototype development efforts.

Review of Prototype System Development Projects

The absorption heat pump prototype development projects are summarized in Table 2. One of these systems, developed by Allied Corporation and Phillips Engineering Company, uses an unconventional organic-fluid working pair: ETFE (ethyl-tetrahydrofurfuryl ether) as the absorbent and R-133a as the refrigerant. The second absorption project, a heating-only system developed by Arkla Industries, Inc., utilizes ammonia and water as working fluids and employs technology used by Arkla in an existing line of residential gas-fired absorption air-conditioners. As indicated, both of these development projects have been carried out

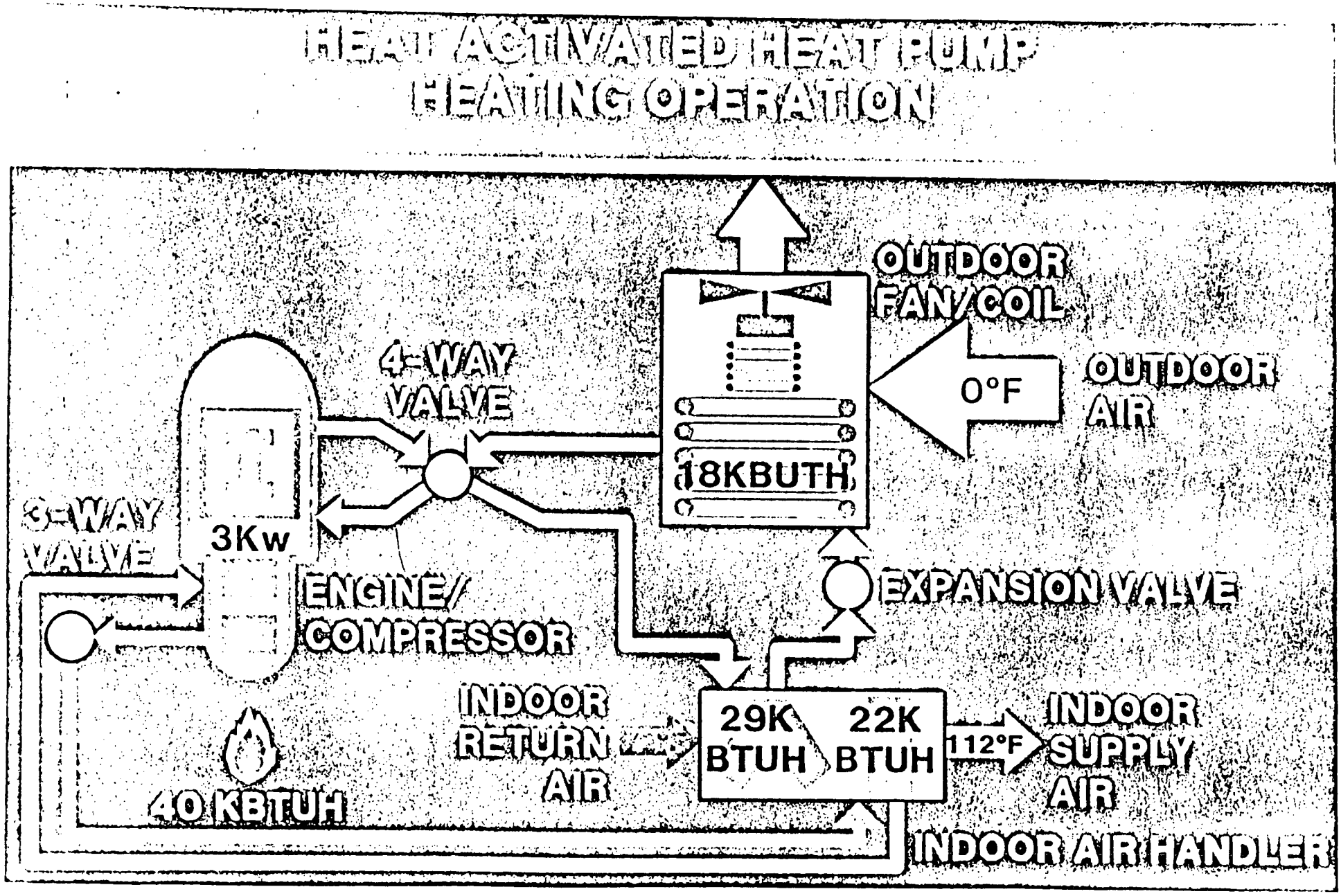

HEAT ACTIVATED HEAT PUMP
HEATING OPERATION
OUTDOOR FAN/COIL
0°F
OUTDOOR AIR
4-WAY VALVE
18KBUTH
3-WAY VALVE
3Kw
ENGINE/ COMPRESSOR
EXPANSION VALVE
INDOOR RETURN AIR
29K BTUH
22K BTUH
112°F
INDOOR SUPPLY AIR
40 KBTUH
INDOOR AIR HANDLER

Figure 3.

Table 1. Comparison of performance potential and risks for HAHP concepts

Concept/Technology	Assessed Risks (technical and business)	Target COP[a] for Prototype Hardware (heating/cooling
Absorption cycle (single stage)	Moderate	1.25/0.50
Gas-turbine-driven (Brayton/Rankine)	Moderate to High	1.30/1.00
Free-piston-Stirling engine driven (Stirling/Rankine)	High	1.60/0.85

[a]Target fuel COP at rating point of 8.3°C (47°F) ambient for heating and 35°C (95°F) for cooling, where fuel COP is defined as the heating or cooling effect divided by the energy value of the fuel used. Target values are steady-state, excluding parasitics.

Table 2. Absorption heat pump projects

Description	Developer	Status/Accomplishments
• Organic-Working Fluids (R-133a/ETFE) Single-Stage Cycle • Heat-Cool • Residential	Allied Corporation[1] (Phillips Engineering Major Subcontractor)	• Lab prototype complete • Achieved 1.25 heating COP[2]
• Ammonia-water Single-Stage • Heating Only • Residential	Arkla Industries	• Lab prototype complete • Achieved 1.25 heating COP[2]

[1]Allied project cosponsored by the Gas Research Institute.

[2]Fuel COP at 8.3°C (47°F). Values are steady-state test results (excluding parasitics) for prototype hardware.

successfully carried out through laboratory prototype testing. Both projects yielded prototype hardware which achieved the target heating COP of 1.25 in laboratory testing. In contrast, the two heat-engine-driven projects selected early for prototype heat pump system development, i.e., the Stirling/Rankine and Brayton/Rankine projects, have experienced serious technical problems and have thus far failed to achieve their prototype performance targets. The two projects are summarized in Table 3.

The free-piston Stirling engine (FPSE) system developed by General Electric Company (Advanced Energy Programs Department, Valley Forge, PA), uses an inertia compressor integrally coupled to the FPSE such that the engine/compressor assembly acts as a single spring/mass resonating system. As indicated, two iterations of prototype hardware failed to meet performance targets and current efforts are more limited, concentrating on technology development aspects of engine/compressor coupling dynamics and engine performance diagnostics.

The second heat-engine projects, scaled for application in commercial buildings, is being developed by AiResearch Manufacturing Company of California, a Division of Garrett Corporation. The system uses a gas turbine (Brayton cycle) engine driving a high-speed centrifugal compressor through a magnetic coupling. Figure 4 shows both the compressor and the Brayton engine side of that rotating assembly. Figure 5 shows a mockup of the complete engine assembly, including the combustor, recuperator, and sink heat exchanger. Prototypes of this combustor/ engine/compressor assembly have been fabricated and shipped to Dunham-Bush and Lennox for incorporation into heat pump system prototypes. However, to date the prototype Brayton engine assembly has only attained a cycle efficiency of 19% versus a 27% goal, despite extended testing and modification efforts. Therefore, assembly and testing of the prototype heat pump systems is being conducted more for operational checkout and to confirm hardware integration than for any meaningful system performance results. The UCC/ORNL subcontract with AiResearch expired at the end of September 1982, but the project is being continued under the GRI contract. It is our understanding that GRI and AiResearch plan to defer the planned

Table 3. Heat engine-driven systems heat pump prototype projects

Description	Developer	Status/Accomplishments
• Stirling/Rankine FPSE-driven spring/mass resonating engine compressor)	General Electric[1]	Two Prototype Iterations • Proto 1 system tested at 1.2 COP_H vs. 1.6 goal
• Heat/Cool		• Proto 2 engine 7 percentage points below η_{cycle} goal
• Residential		• Current UCC/ORNL project has technology focus
• Brayton/Rankine gas-turbine driven	Garrett/AiResearch[2]	• Brayton engine for proto heat pump 8 percentage points below η_{cycle} goal
(high speed rotating engine/ compressor assembly)	(Dunham/Busch & Lennox Subcontractors)	• Proto system assembly/test not for performance
• Heat/Cool		• GRI project near-term focus on engine η_{cycle} improvement
• Commercial (rooftop)		

[1]GE project cosponsored by the Gas Research Institute through 7/82.

[2]Garrett/AiResearch project cosponsored by DOE through 9/82 under a subcontract with Union Carbide Corporation through Oak Ridge National Laboratory (UCC/ORNL).

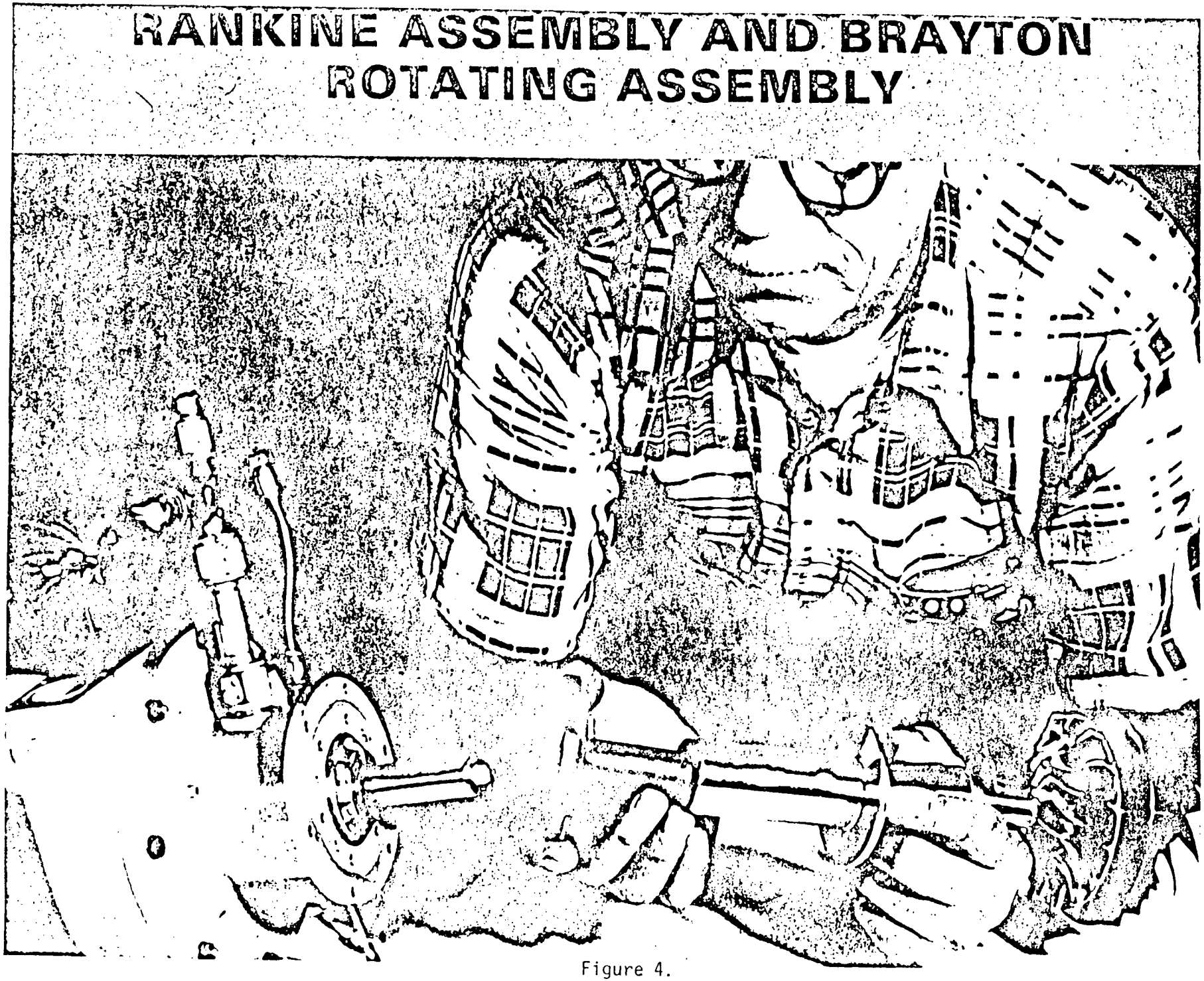


Figure 4.

ENGINE ASSEMBLY MOCKUP

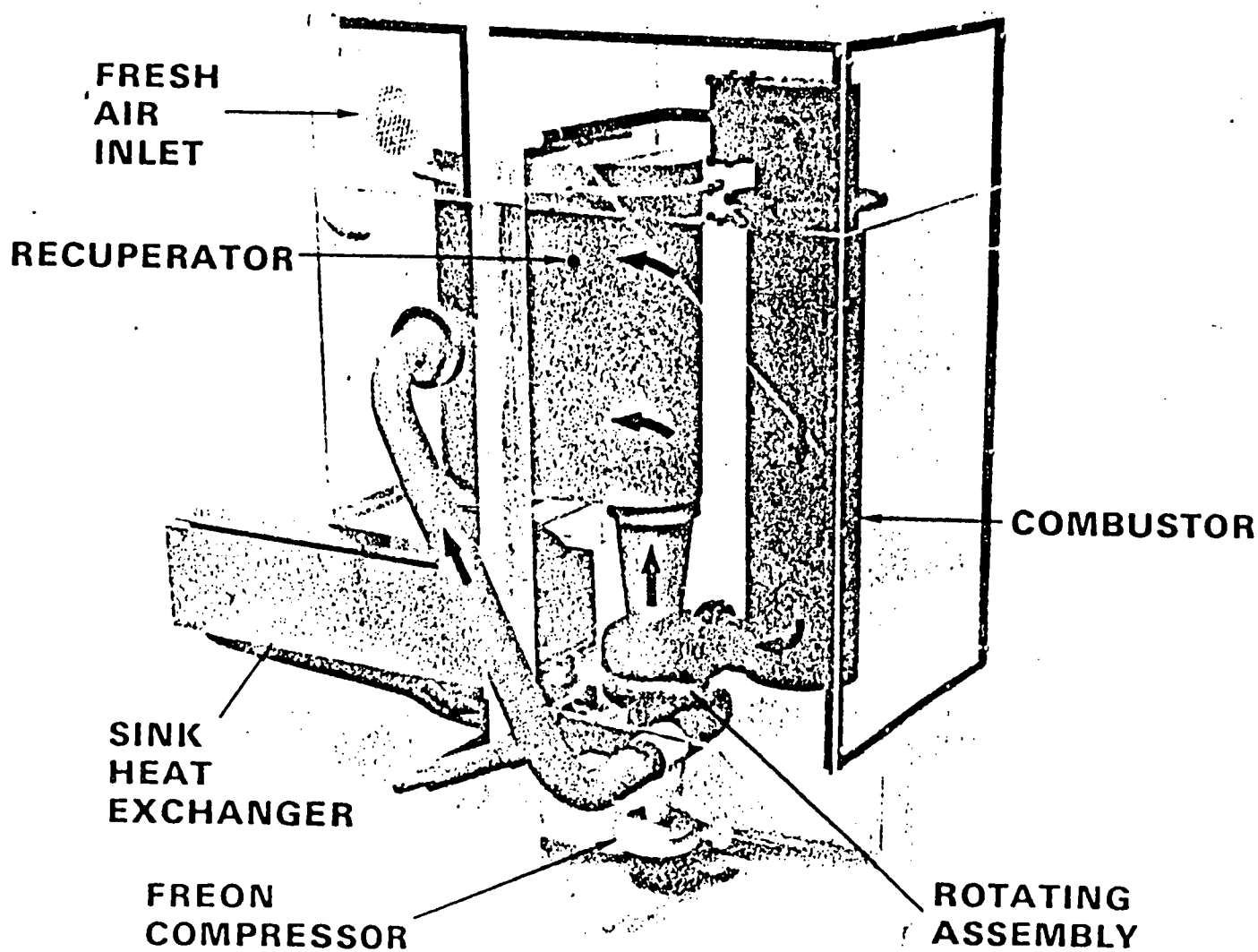


Figure 5.

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"Field Test" phase until another generation of prototype engine hardware is developed and tested at a cycle efficiency approximately five (5) percentage points above the current level (i.e., the prototype engine efficiency target revised to an approximate level of 24%).

Proof-of-Concept Engine/Compressor Projects

In addition, there are two heat-engine-driven projects aimed at laboratory proof-of-concept engine/compressor testing or so-called "breadboard" systems rather than prototype heat pump hardware. The concepts involved were considered to be in an earlier state of development, without sufficient "technology readiness" established to warrant prototype development. These projects are summarized in Table 4.

The breadboard engine/compressor development by Consolidated Natural Gas Research Company with Mechanical Technology Incorporated (CNG/MTI) together with the GE Stirling/Rankine project, will be covered in some detail in following sections of this paper.

The free-piston internal combustion engine/compressor development by Honeywell, Inc. (Technology Strategy Center) with Tectonics Research, Inc. uses a two-stroke, loop-scavenged, linear free-piston engine, designated the Braun Linear Engine, direct-coupled to drive the refrigerant compressor piston. Figure 6 shows a sectioned Braun Linear Engine/air compressor (the center section between the power cylinder and the work output/compressor cylinder houses a rack-and-pinion type balancing mechanism, which provides smooth, vibration-free operation). Figure 7 shows the refrigerant compressor being tested as a component (electric motor-driven).

Perhaps the most significant accomplishment under this project has been in the area of seal development. A proprietary hermetic bellows seal of infinite-life design has been demonstrated in dynamic testing on the engine and in the separate compressor component tests. The final proof of this concept involves testing of the integral engine/seal/compressor assembly under refrigerant conditions representative of heat pump service. The breadboard system for this testing is shown in Fig. 8.

Table 4. Heat-engine-driven proof-of-concept projects

Description	Developer	Status/Accomplishments
• Braun Linear Engine Compressor (free-piston, internal combustion, engine-driving integral compressor)	Honeywell (Tectonics Research, Major Subcontractor)	• Component development complete/novel seal • Lab "breadboard" system: proof-of-concept
• Stirling/Rankine FPSE-Driven (Diaphragm-actuated, hydraulic transmission for coupling to refrig. compressor)	CNG Research (MTI Major Subcontractor)	• Compressor/transmission development complete • FPSE verification • Lab "breadboard" system planned

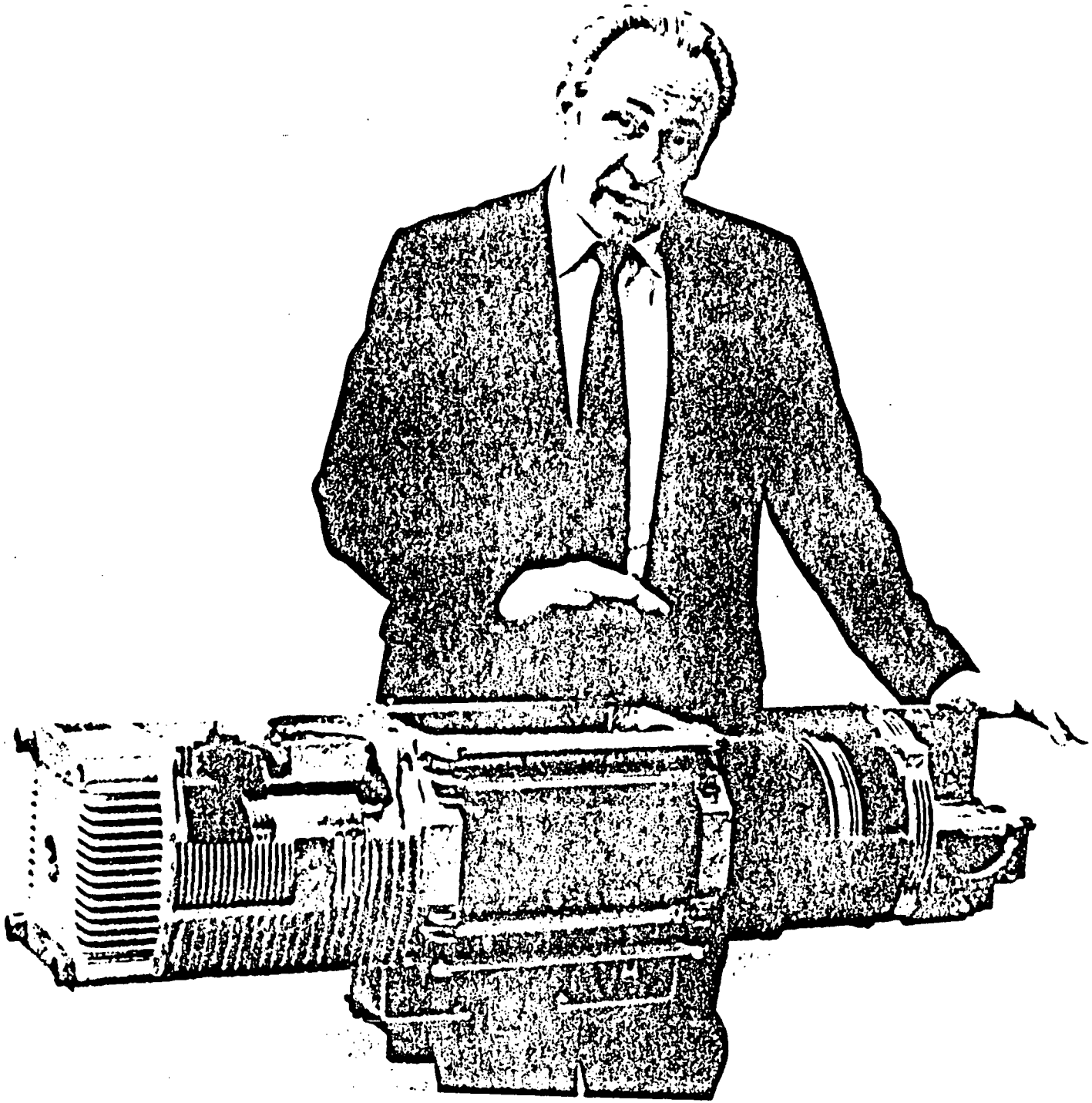


Figure 6.

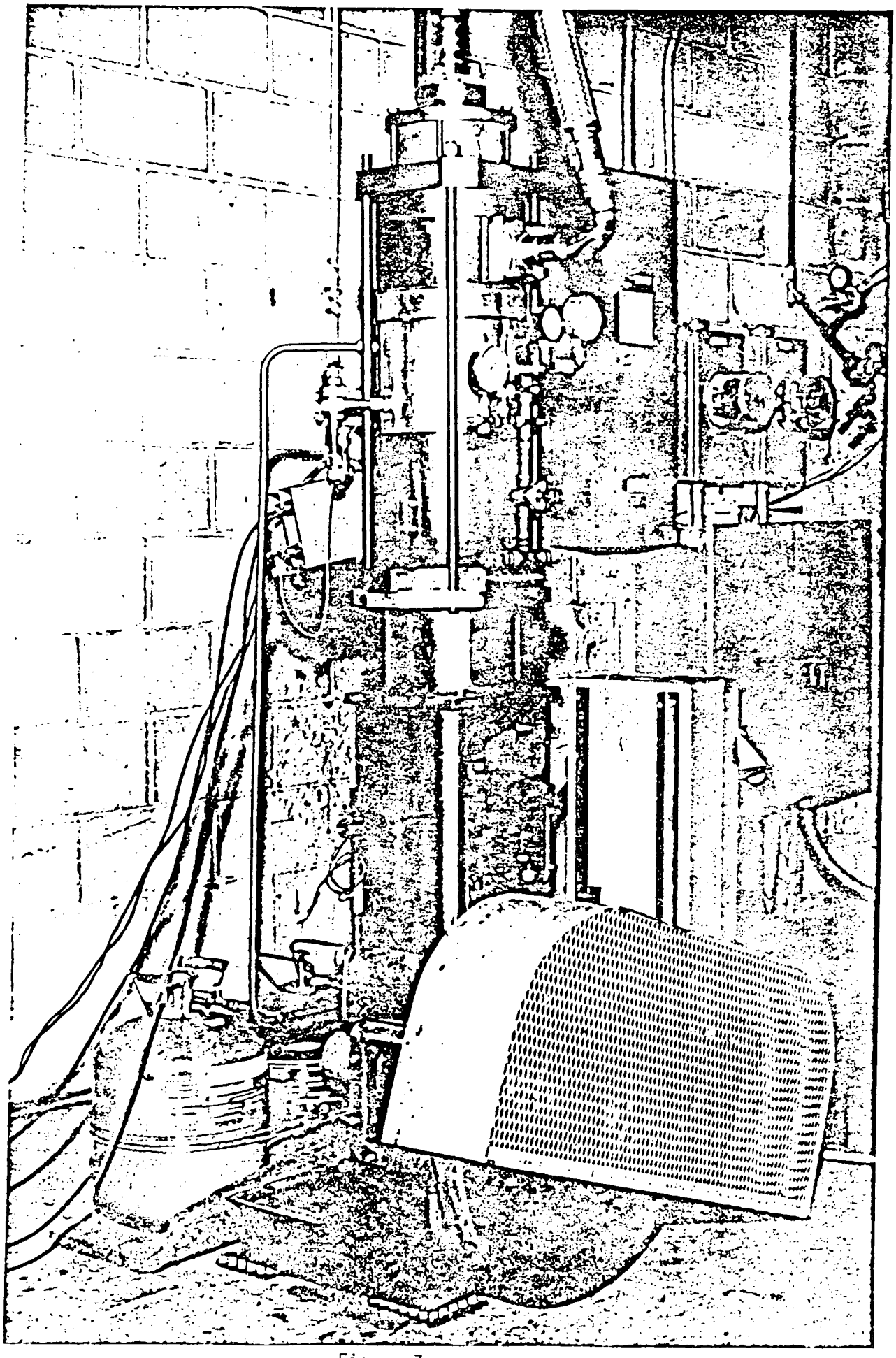


Figure 7.

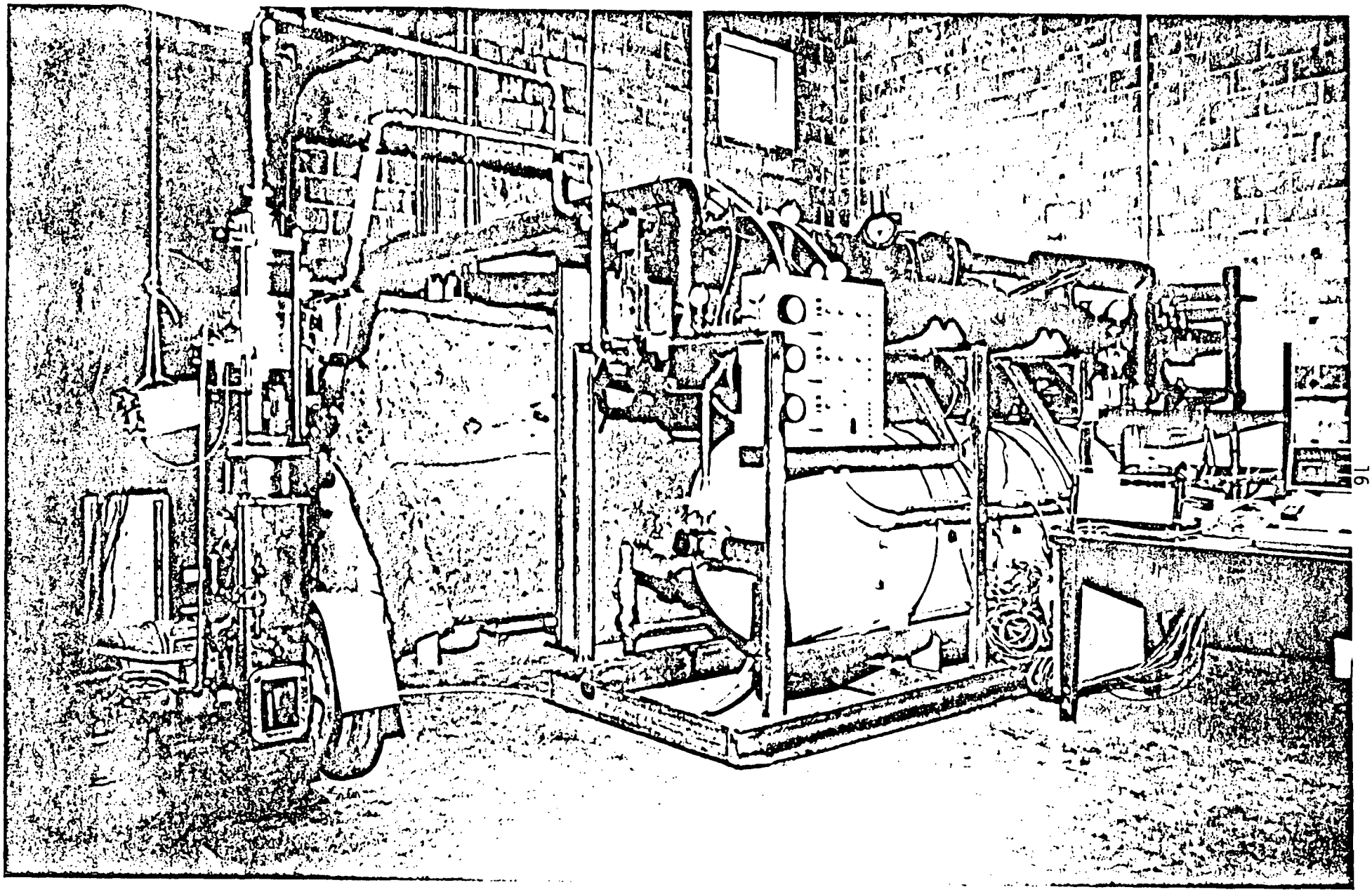


Figure 8.

In addition to the heat-engine-projects being cosponsored by GRI and DOE, GRI is supporting two other HAHP projects, both Stirling engine-driven. Sunpower, Inc. is conducting a development project which involves a free-piston Stirling engine coupled to a Stirling cycle heat pump, the so-called Duplex Stirling HAHP concept. The major advantage of such a machine is that it can be hermetically sealed in a single pressure enclosure and uses a single common working fluid in both heat pump and heat engine. A breadboard system test of the heat engine/heat pump assembly is scheduled for the near future. The other project involves the use of a kinematic Stirling engine to drive a conventional refrigerant compressor. That project is being conducted by Stirling Power Systems of Ann Arbor, Michigan.

Appraisal of Prior HAHP Development Approach

To summarize the heat-activated heat pump projects, our development experience has confirmed the early assessment of the technical risks associated with some of the heat-engine-driven concepts in comparison to the absorption cycle concepts. But more importantly, it has illustrated the pitfalls associated with a "fast track" product development approach when there are still major technical uncertainties. In retrospect, a more measured, sequential approach involving verification of prime mover performance and engine/compressor integration before starting any work on the packaged heat pump system or attempting to analyze consumer acceptance seems to be a more prudent and cost effective approach than the one taken with the GE and AiResearch projects. Of course, there was considerable pressure in the late 1970's when those projects were started to accelerate develoment and commercialization of energy efficient, potentially viable products on the basis that the R&D investment would be quickly returned to the nation in reduced energy consumption. With that pressure reduced due to the present administration's different philosophy, the other two heat engine projects (which were in an early stage in 1981) were restructured to the present proof-of-concept engine/compressor developments. Decisions were also reached at that time to initiate phasedown of the absorption projects and the

AiResearch project. Therefore, the General Electric (GE) project is the only one originally formulated and carried out under the previous "product development" philosophy that has been restructured to continue as a technology development activity.

STIRLING ENGINE-DRIVEN HAHP PROJECTS

Attention will now be focused on the free-piston Stirling engine technology area. The reasons for our interest in this particular heat engine involve several aspects, becides its potential for high efficiency, which would make it particularly well suited for HAHP application. First, the Stirling offers very low noise characteristics compared to a conventional internal combustion (IC) engine, since there are no periodic explosions that have to be muffled and no valve noises. Since it uses external combustion and is thus more readily susceptible to exhaust cleanup, it offers low emissions. The free-piston configuration also offers the apparent advantage of pure linear motion with reduced side loads for low wear and long life potential.

The following two sections describe our experiences to date with the free-piston Stirling engine-driven development projects.

GE Prototype Development Progress and Revised Focus

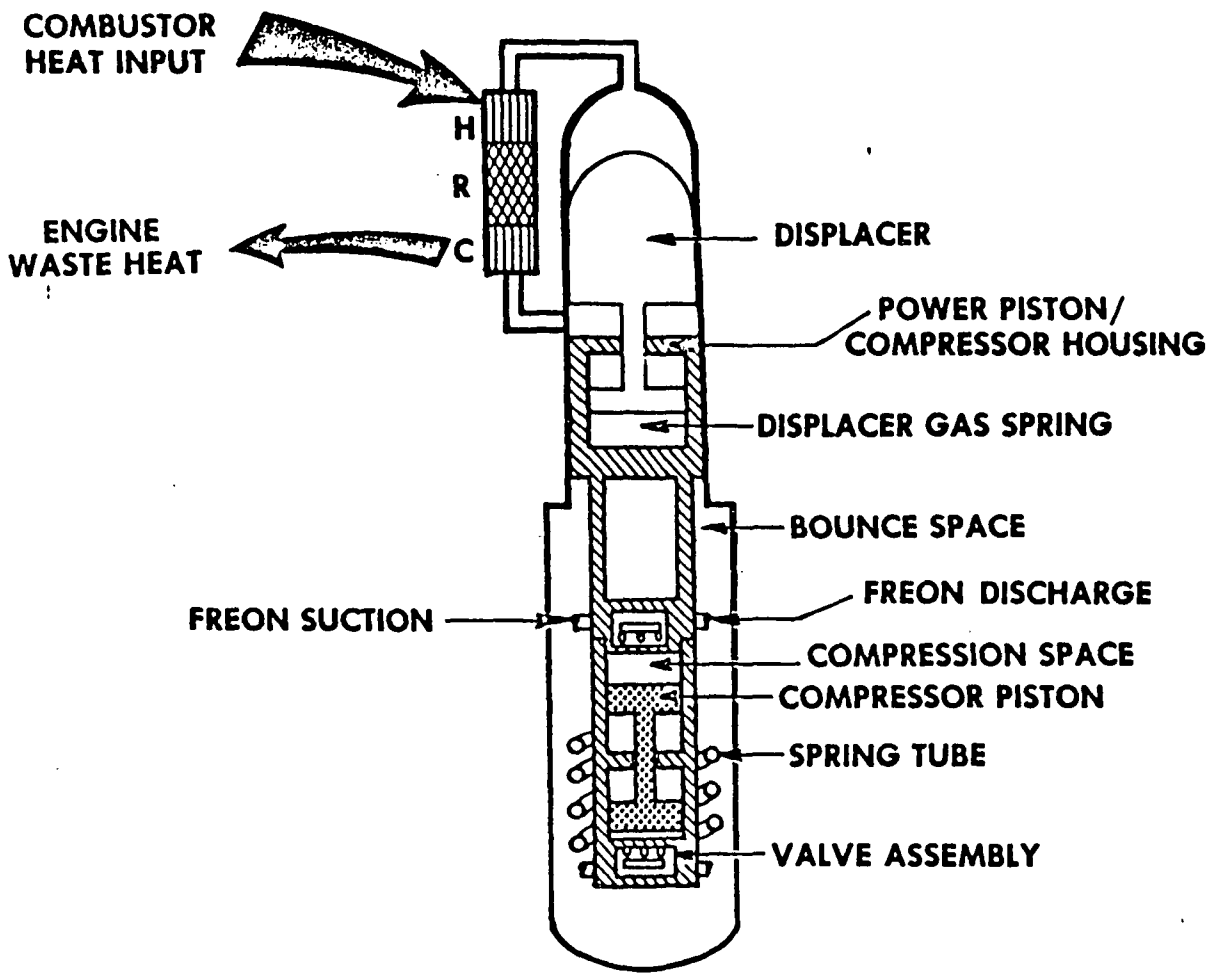
A chrolology of the major events during the course of the GE development work is presented in Wordslide 1. The GE engine/compressor configuration is illustrated schematically in Fig. 9, which includes a summary of the principal characteristics and design features. Heat input provided by the gas combustor provides thermal energy to the Stirling engine working fluid, helium, through the so-called "heater head." The displacer shuttles the helium between the hot and cold spaces thus generating the driving pressure wave for the power piston. The cold space temperature is determined by the cooler, which is water cooled. The regenerator provides thermal energy storage and (due to the large role of stored energy in this cycle) must have high effectiveness. The power piston is directly-connected to the compressor housing with

CHRONOLOGY OF GE DEVELOPMENT PROJECTS

- American Gas Association (AGA) and GE initiated Phase I program to evaluate HAHP's in 1975
  - result was selection of Stirling/Rankine concept for further development
- DOE joined with AGA and GE in 1976 for Phase II contract to accelerate development and demonstration of residential HAHP product
  - Gas Research Institute (GRI) replaced AGA in 1977
- Phase II Program involved two iterations of prototype hardware designated Proto 1 (completed early 1979) and Proto 2 (concluded in 1981)
  - performance/efficiency goals not attained
- Technology Development activities have continued under UCC/ORNL subcontract (Phase III)

Wordslide 1.

PRINCIPAL ENGINE/COMPRESSOR CHARACTERISTICS
GE CONFIGURATION



- Free-Piston Stirling Engine (FPSE)
  helium working fluid
  charge pressure: 60 bar
  frequency: 30 Hz
  T_H = 650°C (1200°F)
  design stroke: 3.3 cm (1.3 in.)
- Linear Inertia Compressor (double acting)
- Hermetic Seal Feature
- Natural Gas Combustor (transpiration cooled)

Figure 9.

the refrigerant being compressed by another free piston (compressor piston) reciprocating within the housing. This is called a linear inertia compressor. The engine displacer and the engine power piston operate with a phase and displacement relationship that creates the Stirling thermodynamic cycle, as shown in Fig. 10. The figure also illustrates the phase and displacement relationship of the compressor piston reciprocating within the housing. Another variable, the refrigerant condition, is controlled by the external conditions imposed on the refrigerant by the building load and outdoor ambient conditions. Figures 11 and 12 are photographs of the first prototype (Proto 1) engine and compressor hardware and Fig. 13 shows the fully-assembled prototype outdoor unit. Proto 1 test results are summarized in Wordslide 2, together with early results from the second prototype (Proto 2) hardware. Because of the Proto 2 engine/compressor performance results and the development priority assigned to the performance improvement efforts, Proto 2 system tests were never conducted. Lack of component testing capability for the engine proved to be a disadvantage in diagnosing the performance problems. Both the combustor and compressor could be and were tested as components prior to integrated testing. However, the engine performance could only be determined from integrated test results. The Proto 2 integrated combustor/engine/compressor assembly in test is shown in Fig. 14.

Wordslide 3 summarizes the final Proto 2 results and the conclusions reached subsequently regarding further work on the GE configuration. The Phase III "Technology Development" subcontract with UCC/ORNL focuses on obtaining component level performance data on the existing engine/compressor assembly. We still do not have sufficient data on hand, for example, to reach an informed decision on the overall viability of the GE engine/compressor configuration and particularly its dynamic sensitivity.

Engine/Compressor Development with CNG/MTI

A chronology of the development project with Consolidated Natural Gas Research Co. and Mechanical Technology, Inc. (CNG/MTI) is presented in Wordslide 4. The objective of the current program is the development

ORNL-DWG 82-15410

OPERATION OF FREE-PISTON STIRLING ENGINE/ FREE-PISTON LINEAR COMPRESSOR

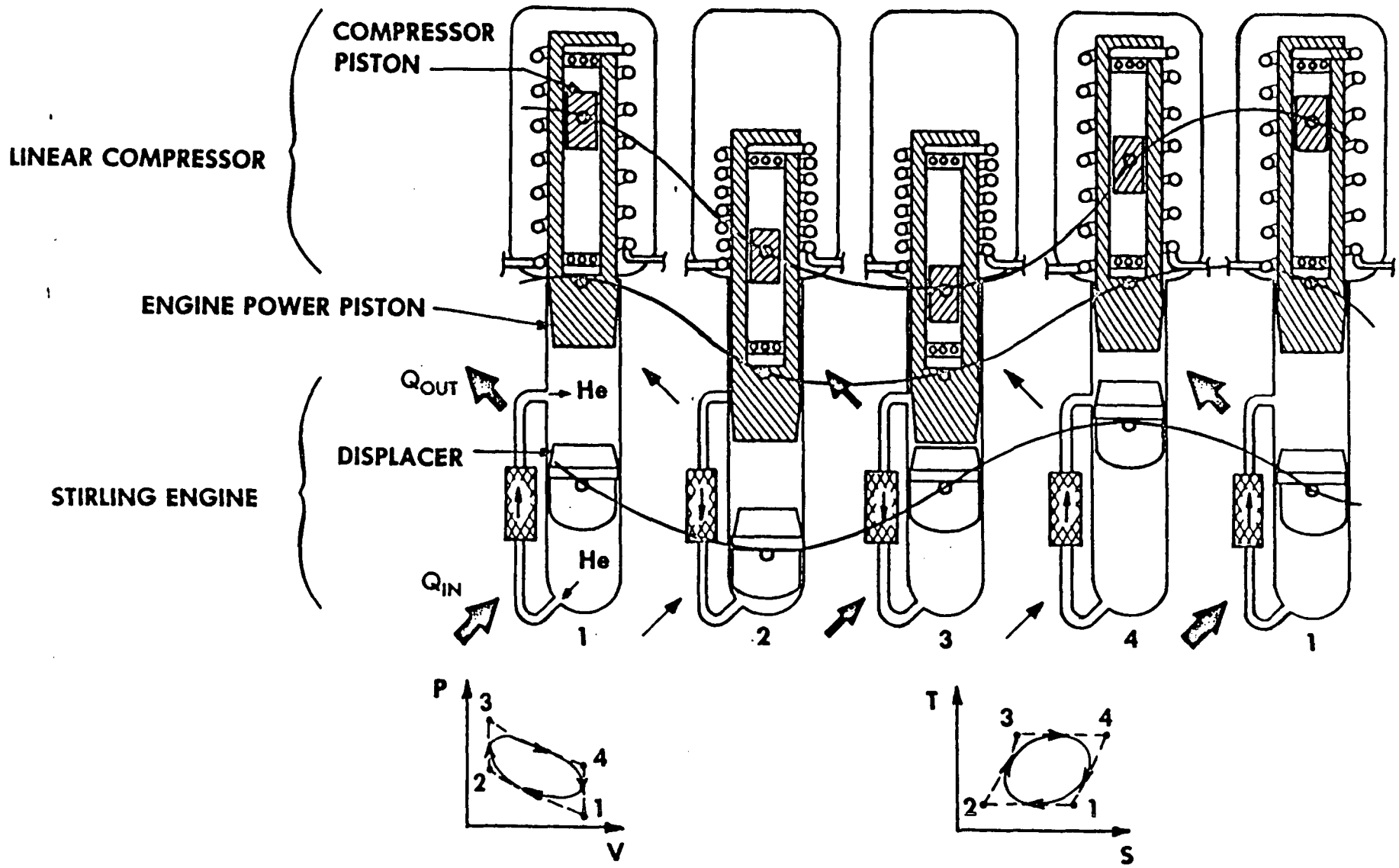


Figure 10.

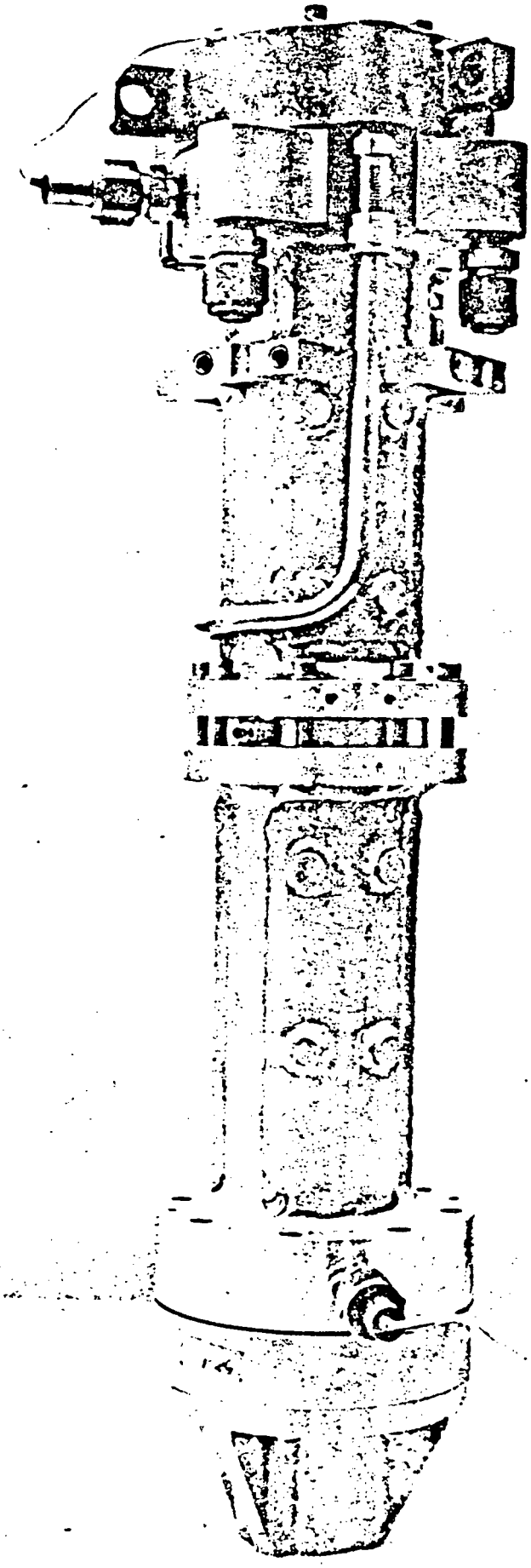
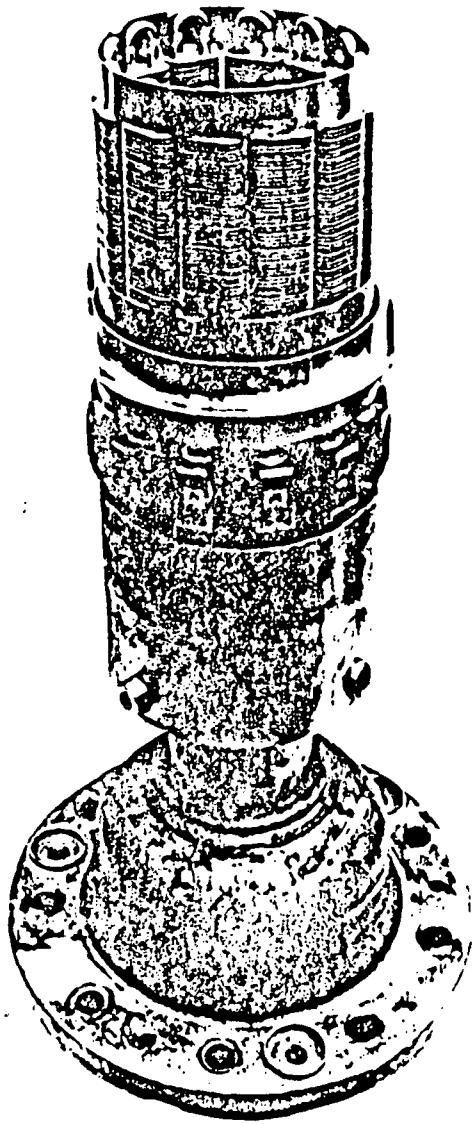


Figure 11.



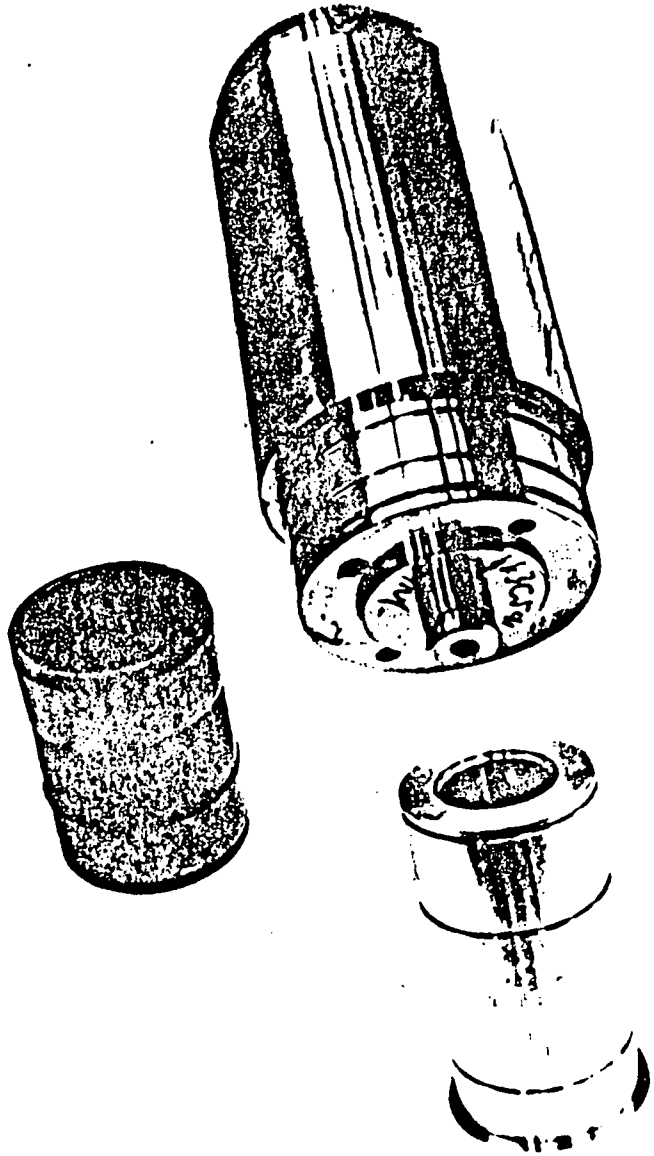
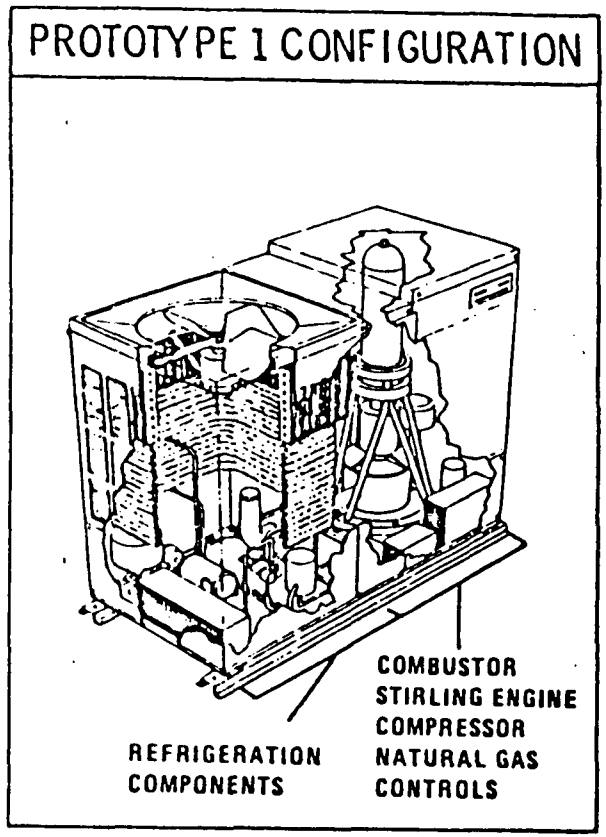
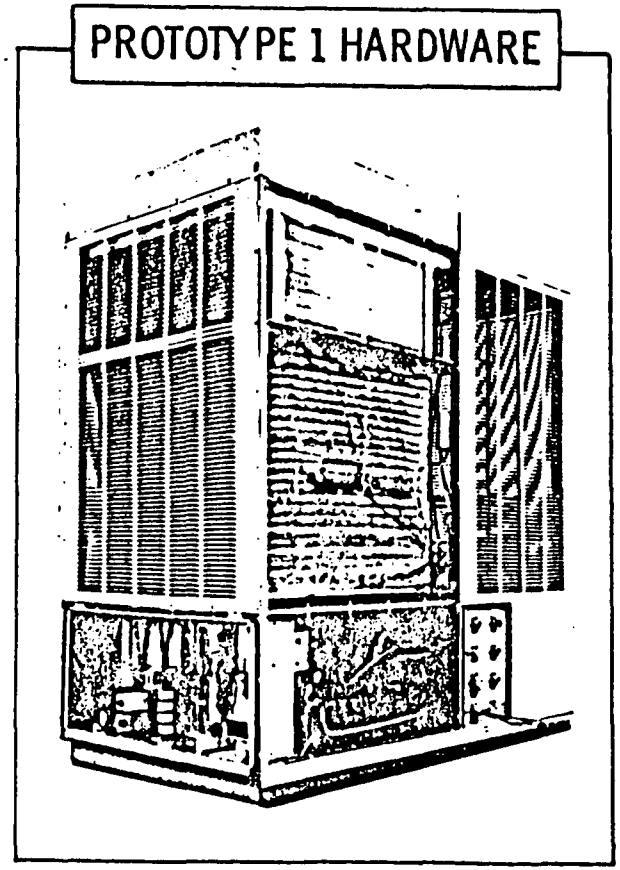


Figure 12.


PROTOTYPE 1 CONFIGURATION
COMBUSTOR
STIRLING ENGINE
COMPRESSOR
NATURAL GAS
CONTROLS
REFRIGERATION
COMPONENTS


PROTOTYPE 1 HARDWARE

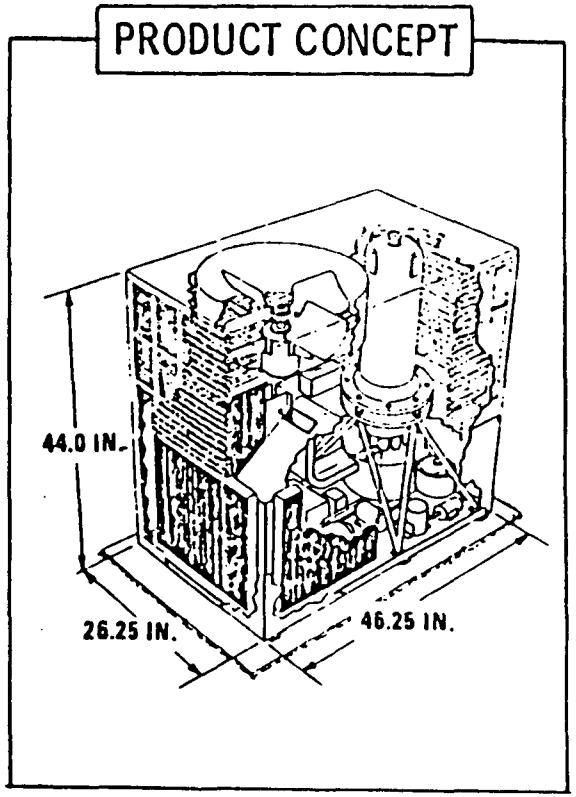

PRODUCT CONCEPT
44.0 IN.
26.25 IN.
46.25 IN.

Figure 13.

GE PROTOTYPE DEVELOPMENT

Phase II Program – DOE/GRI Contract

- Development and testing of Proto 1 completed in early 1979
- Proto 1 demonstrated technical feasibility of FPSE-driven compressor in HAHP lab prototype, but fell short of performance targets
  - System heating COP (fuel based) @ 8.3°C – 1.2 vs 1.6 goal
  - System cooling COP @ 35°C – 0.5 vs 0.85 goal
  - Engine power output 2.1 kW vs 3 kW goal
  - Engine cycle efficiency 20% vs 30% goal
- Design modifications in Proto 2 to increase engine operating frequency and reduce losses yielded disappointing performance results
  - 25% indicated engine efficiency at 2.75 kW output power vs Proto 2 goal of 32% at 3 kW
  - Second gas spring absorbed over 20% of output power, reducing power delivered to compressor

Wordslide 2.

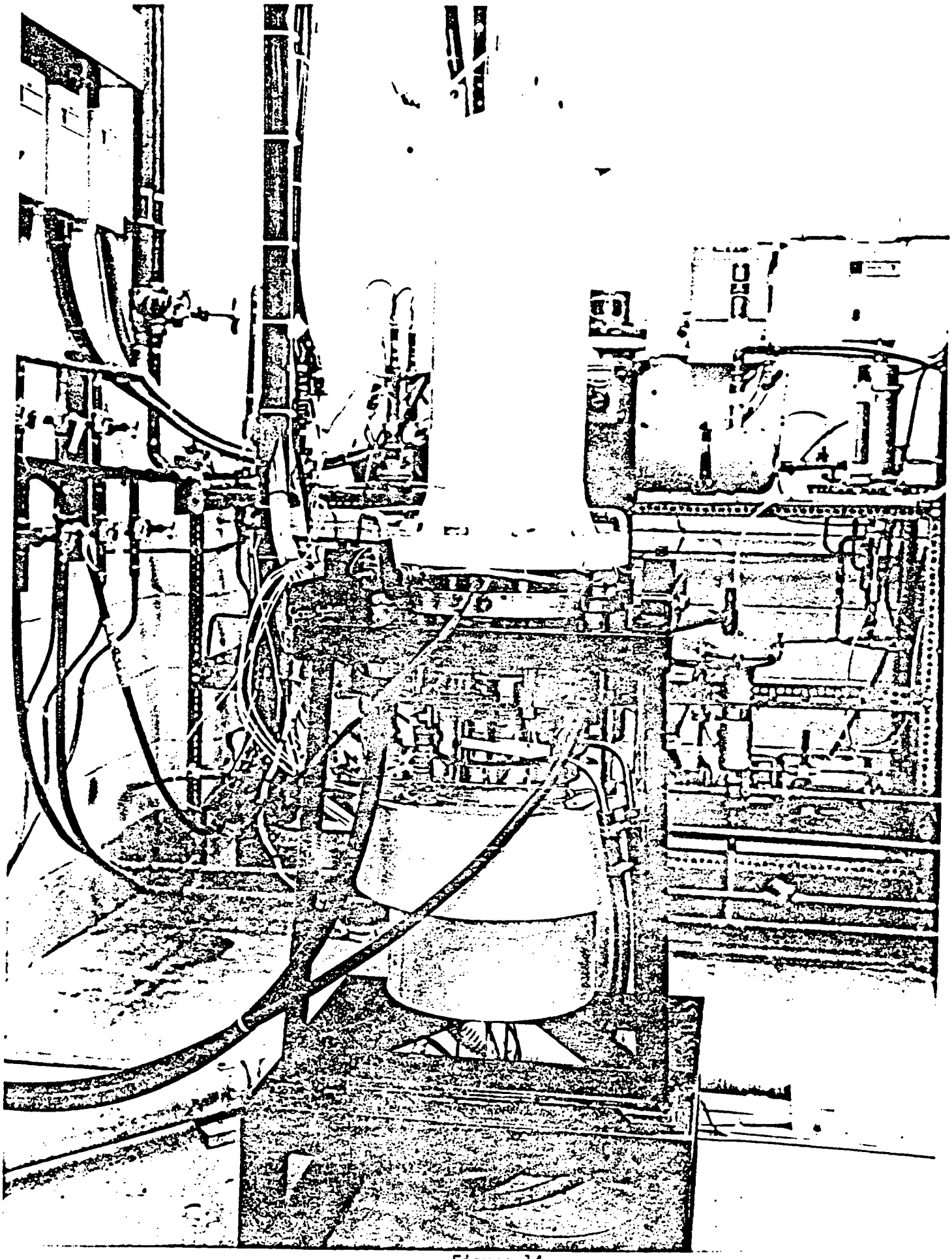


Figure 14.

GE PROTOTYPE DEVELOPMENT
(Continued)

- Subsequent modified FPSE yielded higher efficiency (27-28% indicated), but delivered less power (~ 2 kW)
- Analytical models found to be inadequate for use as design tool for engine modification

- Development and testing of Proto 2 concluded in 1981 (combustor/engine/compressor assembly only, no system level tests)
- Concluded that technology readiness had not been properly established at outset of Phase II "product development" program
- Independent review of program by NASA-LeRC in January 1982 provided guidance for structuring Phase III Technology Development project

Wordslide 3.

CHRONOLOGY OF CNG/MTI DEVELOPMENT

- Engineering Model (EM) FPSE is product of joint CNG/MTI privately-funded engine development program underway at MTI for several years

- UCC/ORNL subcontract with CNG/MTI started June 1980, when HAHP projects still strongly oriented toward product development and commercialization

- In March 1981, UCC/ORNL redirected program and revised scope to focus on diaphragm-coupled refrigerant compressor development and test/evaluation of FPSE-driven (engine/compressor) assembly

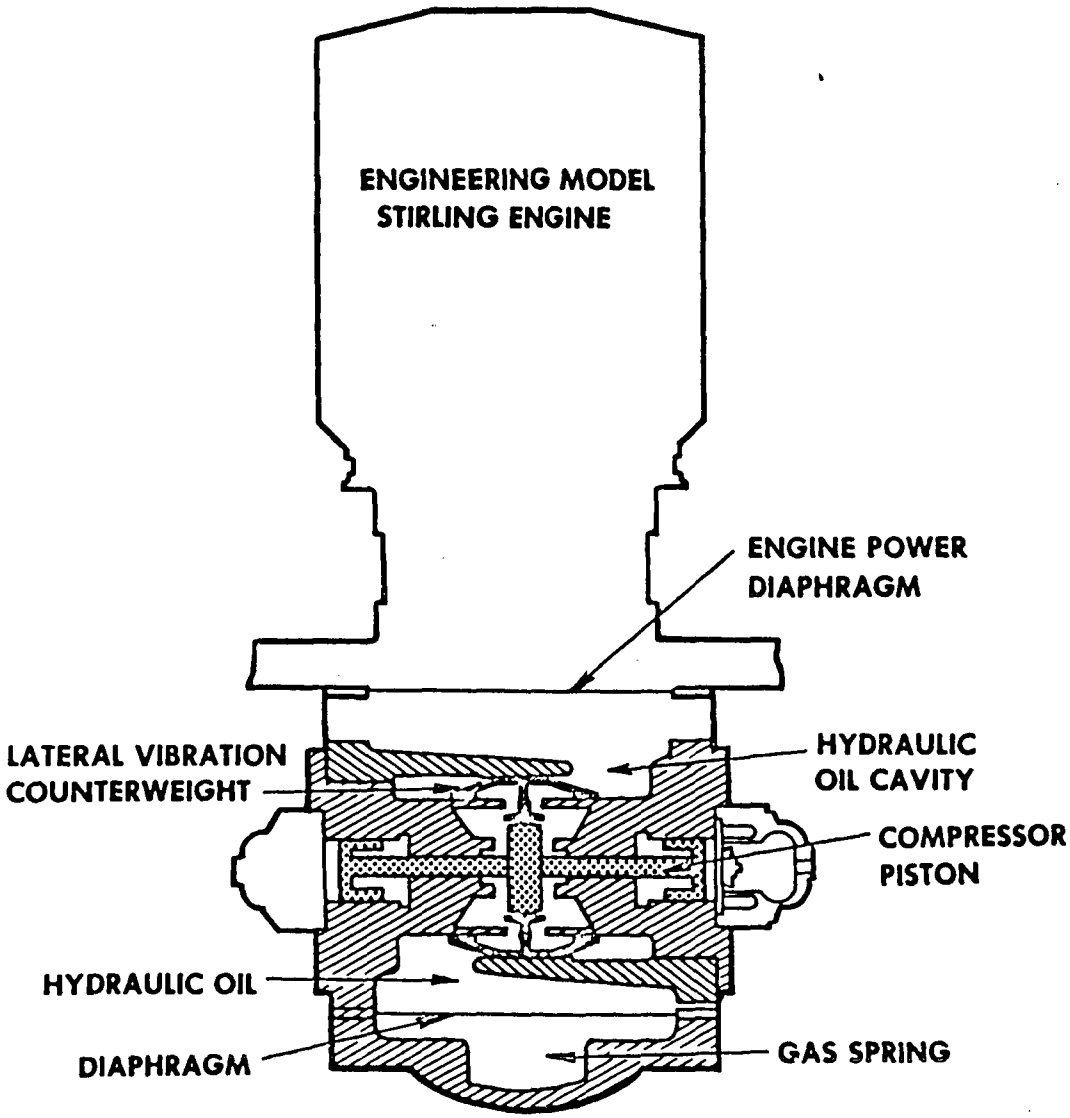
- Current scope of technical effort emphasizes:
  - development of diaphragm-actuated hydraulic transmission for engine-to-compressor coupling
  - compressor development
  - matching EM engine and compressor operating characteristics for adapting in breadboard assembly

Wordslide 4.

of a diaphragm-coupled refrigerant compressor for eventual application to an advanced hermetic FPSE-driven HAHP. The project scope specifically excludes engine development and requires verification testing of the Engineering Model (EM) FPSE performance as a component prior to coupling the engine and compressor.

The CNG/MTI engine/compressor configuration is illustrated schematically in Fig. 15, which includes a summary of the principal characteristics and design features. FPSE operation is similar to that described for the GE engine, although there are certain design features considered proprietary by MTI. The compressor and coupling concept, however, is completely different. In this concept, power is transferred from the engine through a flexible metal diaphragm and hydraulic transmission and delivered to the refrigerant compressor (through the volumetric displacement of the diaphragm, and corresponding displacement of the oil in hydraulic transmission, to the compressor piston). The hydraulic transmission is considered as one subassembly, consisting of the engine power diaphragm, gas spring diaphragm (restoring force function), transverse vibration balancer (counterweights), and the hydraulic oil. The compressor subassembly includes the cylinder heads, valves, pistons, and the refrigerant gas. The three subassemblies — engine, transmission, and compressor — form a coupled resonant system. One of the potential advantages of this configuration over the GE configuration is reduced dynamic complexity. The use of the power-transfer diaphragm has eliminated one degree of freedom in the resonant system, which should improve its operating stability and control. Of course, lifetime of the diaphragm, which must undergo some 10^9 stress reversal per year, becomes a crucial question: present evidence, including operating experience in England with diaphragm-sealed Stirling engines, strongly indicates that diaphragm material and designs can be selected to give infinite fatigue life. Figures 16 and 17 are photographs of the EM engine hardware which show that there are also some differences in FPSE design features, notably the monolithic heater head configuration.

PRINCIPAL ENGINE/COMPRESSOR CHARACTERISTICS
CNG/MTI CONFIGURATION



- Free-Piston Stirling Engine
  - Engineering Model (EM)
  - helium working fluid
  - charge pressure: 60 bar
  - frequency: 60 Hz
  - T_H = 760°C (1400°F)
- Natural Gas Combustor
- Resonant Piston Compressor (double acting)
- Power-Transfer Diaphragm (reduced dynamic complexity)
- Hydraulic Transmission of Force/Displacement to Refrigerant Compressor
- Hermetic Seal Feature

Figure 15.

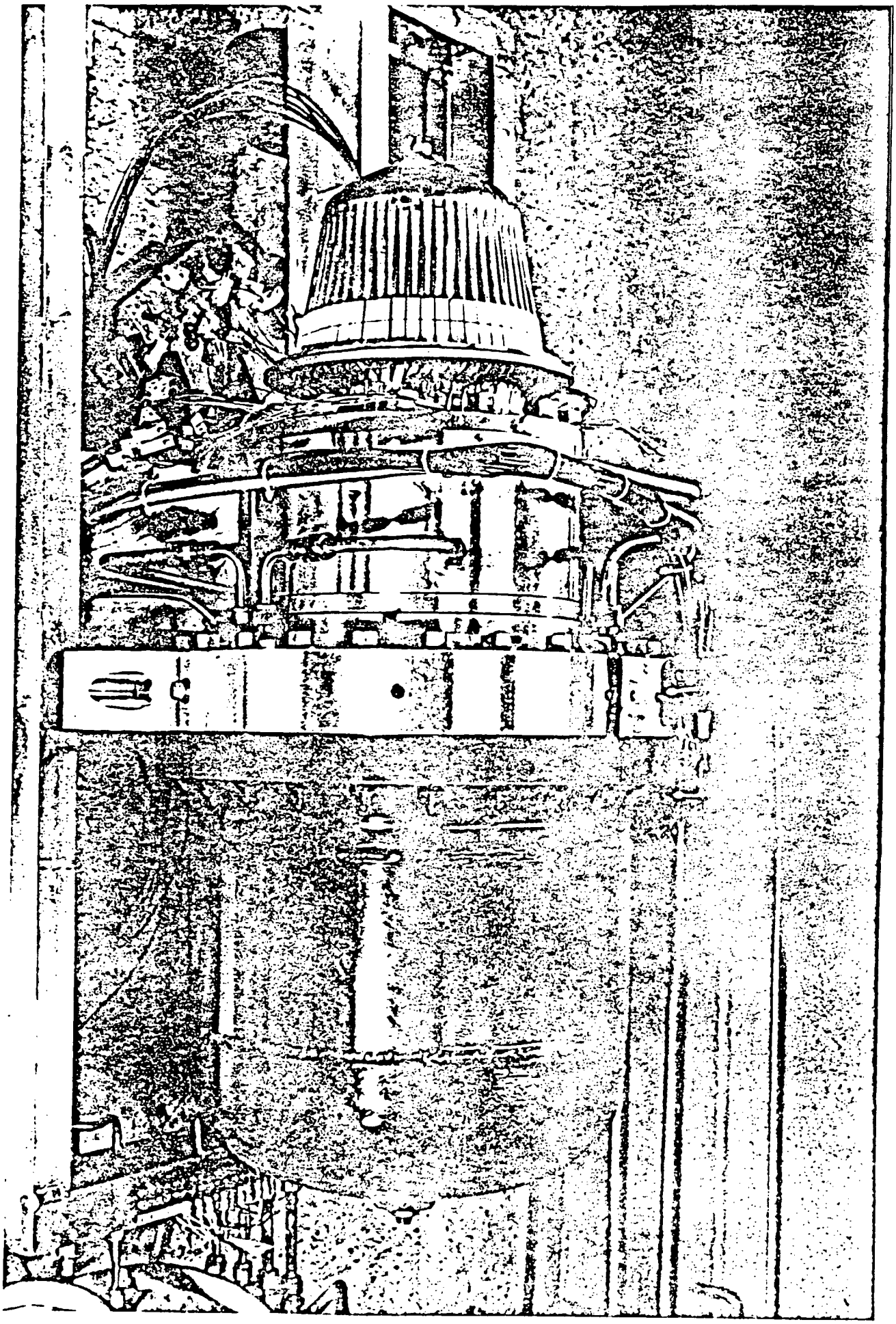


Figure 16.

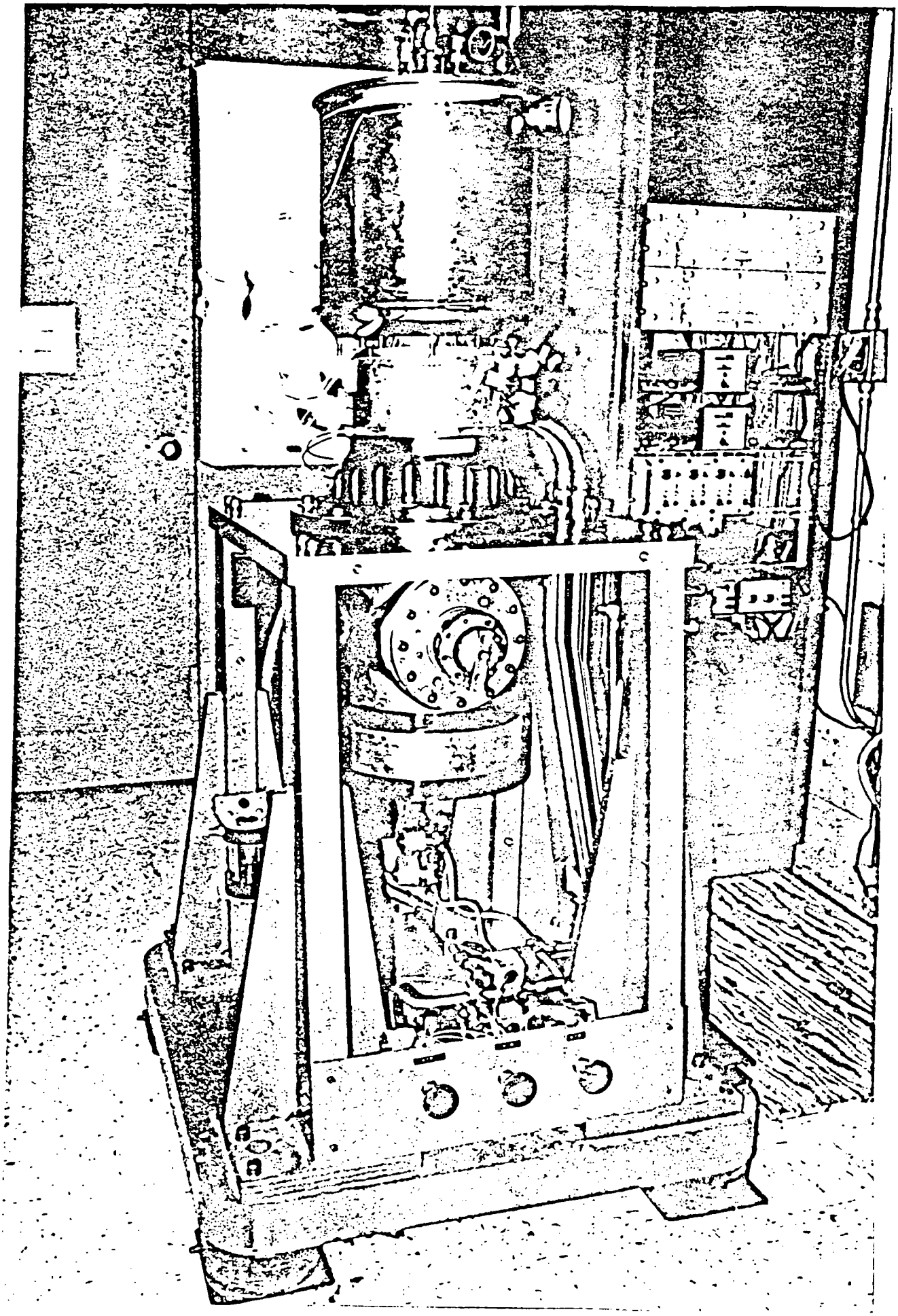


Figure 17.

Wordslide 5 summarizes the current status of the CNG/MTI project. The next year is critical in establishing the technical viability of this new configuration with regard to thermal performance and operating stability and control. However, even if test results are positive, key technology issues will remain to be solved on durability, reliability, and attaining all of these desired characteristics at reasonable manufacturing cost.

Technology Issues and Development Approach

Throughout the earlier sections of this paper, several issues were identified with regard to applying free-piston Stirling technology to HAHP development. What we perceive to be the key issues seem to fall into three general categories, as summarized in Table 5.
The two hardware development projects just described are not our only efforts at resolving these issues. In 1981 we formulated a more generic plan of work in this area, a plan which we began to implement this year. The plan is diagrammed in Fig. 18. The three main elements of the technology development program are: 1) determining the state-of-development of the free-piston Stirling engine itself (prime mover development;) 2) engine/compressor coupling and related dynamic design issues (possibly including compressor development or dynamic seals); and 3) development and validation of analytical design tools. The program will take maximum advantage of technology being developed at NASA-LeRC, MTI, Argonne, and JPL under other DOE programs (Automotive Stirling, ECUT/previously Fossil Energy, Solar, etc.).

We have started a survey and assessment of available FPSE performance measurements (both published and unpublished). The assessment should determine whether there is sufficient experimental data available to permit establishing a state-of-the-art (SOA) "benchmark" on FPSE thermal and mechanical efficiency. The survey will provide the beginnings of an experimental data base on FPSE system and component performance which can be used for validation of analytical codes. The survey may also provide some preliminary comparisons of engines operated

FPSE-DRIVEN COMPRESSOR DEVELOPMENT
(CNG/MTI Subcontract)

- UCC/ORNL scope with CNG/MTI specifies:
  - use of EM engine (when available) in breadboard assembly
  - prerequisite tests to verify that it will operate over HAHP operating range
- EM Engine Verification Testing now underway
- All design work and matching analyses on compressor, hydraulic transmission, and breadboard engine/compressor assembly completed June 1982 and all component hardware ordered
- Compressor Component testing and Breadboard System Testing should commence by end of 1982

Wordslide 5.

Table 5. Current appraisal of key issues
FPSE/compressor technology

Performance Efficiency	Cost	Durability & Reliability
• FPSE efficiency (SOA and potential with mature technology	• Equipment cost premium vs. operating cost savings	• Design life vs. heat pump requirements
• Engine/compressor integrated performance		• Service calls/maintenance requirements
– dynamic sensitivity, stability, controls		
– best configuration		
• Analytical tools (dynamic and thermal		

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SUBPROGRAM LOGIC DIAGRAM

FREE-PISTON STIRLING ENGINE (FPSE)/COMPRESSOR TECHNOLOGY

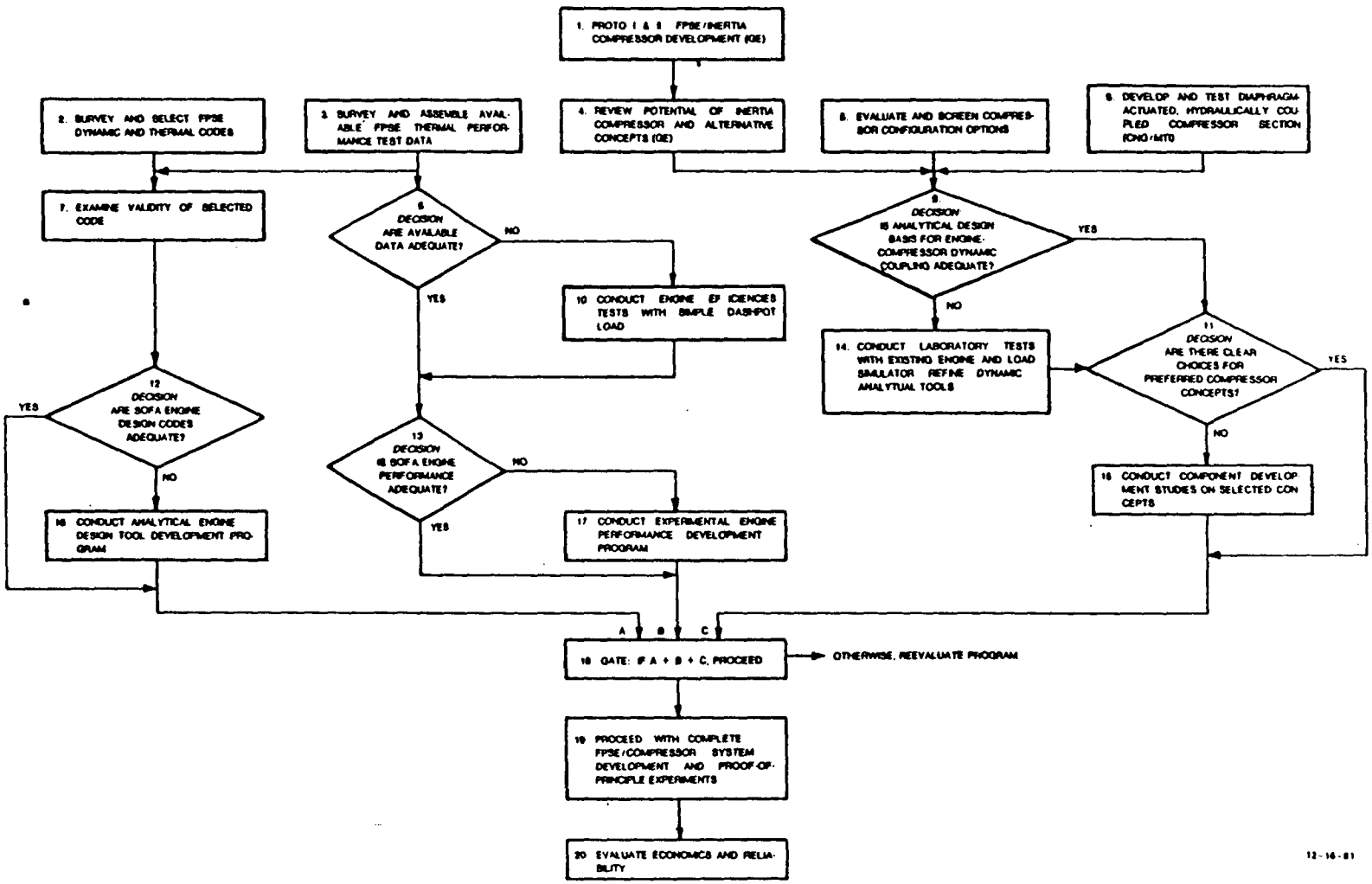

Figure 18.

with different types of loads (simple dashpot, alternator, inertia compressor). Analysis of the measured data may yield some useful information about the effect that the load characteristics have on FPSE performance. If there are sufficient data to establish SOA engine performance, then this will be compared with the performance "target" required for economic viability (in the engine-compressor application). A separate program analysis task would be required to reexamine the nominal 30% engine efficiency target set for the development program several years ago and to confirm or modify it as appropriate.

A survey and assessment of FPSE dynamic and thermodynamic analytical codes is also underway. It is known that the most complex codes (so-called third order codes) do not anways give the best results; therefore, we will attempt to define what level of sophistication is necessary for design purposes and thereby to select one or two candidate FPSE codes for validation against the experimental data available. Emphasis is being placed on FPSE dynamic codes and methods for handling interaction between the mechanical/gas dynamics and the Stirling cycle thermodynamics. Much effort has gone into development of thermodynamic cycle codes for kinematic Stirling engines and some comparative analyses of those computer codes have already been reported.

We also propose design and development of a versatile test load device to aid in understanding the complex gas/mechanical dynamics of the FPSE-load system (including interaction with Stirling cycle thermodynamics) and to simulate FPSE/compressor coupling. Testing would provide the required experimental data on dynamic sensitivity and "matching" of the driven load (i.e., refrigerant compressor) to the FPSE output characteristics.

New project activities started this year under this generic technology effort are summarized in Wordslide 6. We plan to effect close coordination between these activities and the hardware development work during the coming year. The plan focuses on issues in the performance/efficiency category. However, the plan recognizes that other issues related to life

STIRLING/RANKINE TECHNOLOGY

NEW DEVELOPMENT ACTIVITIES

ORNL Inhouse – FPSE Hardware and Analytical Tools Assessment

- Survey/evaluate dynamic and thermal codes
- Document available FPSE experimental results

NASA-LeRC Interagency Agreement

- Experimental tests to provide data for model validation (FPSE/component performance)
- Assess variable load-absorption devices for FPSE
- Endurance testing

Argonne National Lab – Cosponsored with DOE/ECUT Program

- Oscillating flow tests to provide heat transfer, pressure drop correlations for analytical models

Wordslide 6.

requirements and cost must be a continuing concern in the development process because of their critical importance in the eventual application in HAHP's.

CONCLUSIONS

This paper represents an attempt to describe where we have been, what we have learned, and where we are going in development of technology for application in future heat-activated heat pumps. Emphasis has been placed on Stirling engine-driven HAHP technology, with its many challenging development problems, because it was early identified as having high potential for this application and that positive assessment (of its high efficiency potential and other needed attributes) continues. Based on the review presented in the preceding sections, we offer the following summary observations and conclusion.

- In retrospect, the previous "Product Development" efforts on engine-driven HAHP's were premature; i.e., they were undertaken before the technology was sufficiently advanced to warrant such an approach.

- The technical problems are now better understood and can therefore be broken down into more manageable technology development tasks or projects.

- It is still not clear how best to actuate a heat pump cycle with a free-piston Stirling engine. Until this load-engine coupling and control issue is better understood and preferred engine/transmission/compressor configurations identified, it will be difficult to undertake or properly focus R&D on such critical issues as durability, reliability, or cost.

- To the extent feasible, we plan to use available engine technology rather than to develop it ourselves, so that this program can concentrate its resources on the issues related to application in HAHP's.

- The free-piston Stirling engine-driven HAHP is still an attractive and interesting equipment option for the future, but it continues to involve high risks (technical and business), even after several years of development work.

We view this conference as an excellent forum in which to present this information, so that we might obtain constructive feedback from you. Therefore, having presented our assessment and current views on the issues and our planned development approach, we ask for your guidance and input.